ISSN 2395-1621

Numerical Investigations on Characteristics of stresses in U Shaped Metal Expansion Bellows

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ABSTRACT

Metal expansion bellow is a mechanical device for absorbing energy or displacement in structures. It is widely used to deal with vibrations, thermal expansion, and the angular, radial, and axial displacements of components. The main objective of this paper is to perform numerical analysis to find various characteristics of stresses in U-shaped metal expansion bellows as per the requirement of vendor and ASME standards. In this paper extensive analytical and numerical study is carried out to calculate the different characteristics of stresses subjected to internal pressure varying from 1MPa to 2MPa in U-shaped bellows. Finite element analysis by using Ansys14 is performed to find the dynamics characteristics of U shaped metal expansion bellows. Finally, the results of the analytical analysis and finite element method (FEM) show a very good agreement. The fatigue analysis is done for the given U shaped metal expansion bellows which shows the good agreement with the FEM results. The results of the present work could be used as a basis of designing a new type of the metal bellows.

Keywords— **Metal expansion bellows, finite element method(FEM), fatigue anlaysis, membrane stress**

ARTICLE INFO

Article History

Received :18th November 2015

Received in revised form :

19th November 2015

Accepted : 21st November , 2015

Published online :

22nd November 2015

I.INTRODUCTON

Metal Bellows are structural component in which a wavy shape is formed on surface of a circular tube to introduce elastic property. Expansion joints used as an integral part of heat exchangers or pressure vessels shall be designated to provide flexibility for thermal expansion and also to function as a pressure containing element. Normally metal bellows are used as an expansion joint in shell and tube heat exchanger. It deals with vibrations, thermal expansion, and angular, radial axial displacements of components. Its present applications are in AC equipment, industrial plants, hose pipes, vacuum systems and aerospace equipment's.

Limited amount research work has been carried out by some researchers working in the area of the expansion joint for shell and tube heat exchanger. Their work has been reported by performing industrial survey (viz. Alfa Laval India Ltd. Pune) and exhaustive literature review through earlier published research work, journal papers and technical reports. Many design formula of bellows can be found in ASME code [1]. And the most comprehensive and

widely accepted text on bellows design is the Standards of Expansion Joint Manufactures Association, EJMA [2]. Number of pilot and test experiments has been performed for analysis of AM350 steel bellows by Sheikh et al [3]. As bellow is exposed to marine atmosphere for more than 13 years of period which leads to pitting effect, hence the determination of dynamic characteristics of beam finite elements by manipulating certain parameters on commercial software was done by Browman et al [4]. In comparison with semi-analytical, methods has potential of considering axial, bending and torsion degrees of freedom at same time, and rest is modeled by finite elements. In this experimental results are also verified. The effect of the

elliptic degree of Ω-shaped bellows toroid on its stresses is investigated by Li [5]. In
addition, Becht [6] has investigated the fatigue behavior of expansion joint bellows. The results of Ω-shaped bellows with elliptic toroid calculated stresses correspond to experiments. The elliptic degree of Ω-shaped toroid affects the magnitude of internal pressure-induced stress and axial deflection-induced stress. Especially, it produces a great effect on the pressure-induced stress. To maintain the fatigue life of toroid bellows, during manufacturing process toroid elliptic degree must be reduced. EJMA stresses for unreinforced bellows are evaluated by Becht [6]. Using linear axisymmetric shell elements parametric analysis is conducted. Finite element analysis is carried out using commercial code. Meridional stresses due to internal pressure and displacement are accurate. Bellows forming process is done after evaluating effective parameters by Faraji, et al. [7]. FEM results are compared with Analytical solutions. Faraji, et al. [8] used a commercial FEM code ABAQUS Explicit to simulate manufacturing process of metal bellows. Forming of different shapes of tubular bellows using a hydro-forming process is proposed by Kang, et al. [9]. The conventional manufacturing of metallic tubular bellows consists of four-step process: deep drawing, ironing, tube bulging, and folding. In their study a single step tube hydro-forming combined with controlling of internal pressure and axial feeding was proposed. These reviewed papers show that there are needs for rigorous analysis and forming parameters of bellows. It is stated that the Ω-shaped bellows have much better ability to endure high internal pressure than common U-shaped bellows. Metal bellows have wide applications in piping systems, automotive industries, aerospace and micro-electromechanical systems. Kang et al. [10] have developed a micro-bellows actuator using micro-stereo lithography technology. Numerous papers have dealt with various aspects of bellows except for forming
process; Broman et al. [4] have determined dynamic characteristics of bellows by manipulating certain parameters of the beam finite elements, Jakubauskas and Werner [11] have considered the transverse vibrations of fluid-filled double-bellows expansion joints. Jha et al. [12] have investigated the stress corrosion cracking of stainless steel bellows of satellite launch vehicle propellant tank assembly. Zhu et al. [15] have investigated the effect of environmental medium on fatigue life for u-shaped bellows expansion joints. However, few papers have studied the manufacturing process of the metal bellows. Wang et al. [14] have developed a new process for manufacturing of expansion joint bellows from Ti–6Al–4V alloys with high degree of spring back. Wang et al. [14] have used gas pressure instead of fluid pressure, because the process was done in high temperature ambient. Kang et al. [10] has investigated forming process of various shapes of tubular bellows using a single-step hydro forming process. Lee [13] has carried out parametric study on some of the forming process parameters of the metal bellows by finite element only. He has mentioned that, in general, metal bellows are manufactured in four stages: deep drawing, ironing, tube bulging and folding.

From literature survey, it is seen that many researcher worked on study and applications of different types of bellows under various working conditions and their comparison, their manufacturing processes and few are working on fatigue life enhancement. But investigations on need for selection of proper material of bellow for given application, their proper design, stresses induced, fatigue life analysis, prediction of failure, investigations on various characteristics of different bellows and vibration effect is essential.

II. PROBLEM FORMULATION & OBJECTIVE

As per literature and industrial survey, it is seen that bellow is one of the most important element in the expansion joint and has the function to absorb regular as well as and irregular expansion and contraction of the system. Bellow requires high strength and good flexibility, which can be achieved by good design and proper manufacturing method. The design referred from EJMA, requires proper configuration selection which makes it difficult. The metal bellows are manufactured with different methods like forming, hydro-forming, bulging, drawing, deep drawing, which depends on application. The material used for bellows are normally stainless steel, in rare case Inconel and Aluminium. Different shape of bellows are U-shaped, semi toroidal, S-shaped, Flat, stepped, single sweep and nested ripple. As per discussion with experts working in same field, it is observed that the concept of study in this paper need detailed understanding of proper design and investigations on selection of materials and shapes, vibration effect, joining of bellows to shell, stresses, flow analysis, fatigue life analysis and prediction of failure. Hence this work focuses on selection of materials of bellows for the given application, their proper design, and determination of characteristics of bellows, fatigue life analysis and prediction of failure.

III. DETERMINATION OF CHARACTERISTICS OF BELLOWS BY ANALYTICAL ANALYSIS

The bellows is a very unique component of a piping system. It must be designed strong enough to accommodate the system design pressure, as well as, flexible enough to accept the design deflections for a calculated number of occurrences, with a minimum resistive force. In order to understand the static and dynamic behavior of metal
expansion bellows as shown in Fig.5, it is necessary to study the selection of materials of bellows for the given application, basic fundamental, their proper design and working. The different mechanical properties and design parameter for bellow under consideration are shown in Table 1.

TABLE I

DIFFERENT DESIGN PARAMETERS

Expansion Joint Material	Notation	SA – 240 321
Material UNS Number		S32100
Bellows Design Allowable Stress	S	129.65 N/mm^2
Bellows Ambient Allowable Stress	S_a	137.89 N/mm^2
Bellows Yield Stress	S_y	157.39 N/mm^2
Bellows Elastic Modulus at Design Temp	E_b	183090 N/mm^2
Bellows Elastic Modulus at Ambient Temp	E_o	195121 N/mm^2
Poisson's Ratio	ν_b	0.300
Bellows Material Condition		Formed
Design Cycle Life, Required number of cycles	N_{req}	7000
Design Internal pressure	P	1.099 N/mm^2
Design temperature for Internal Pressure		190 ^{o}C
Bellow Type		U- Shaped
Bellows inside diameter	D_B	131.000 mm
Convolution Depth	W	8.000 mm
Convolution Pitch	Q	8.000 mm
Expansion joint opening per convolution	ΔQ	0.2985 mm
Total number of convolutions	N	10
Nominal thickness of one ply	T	0.300 mm
Total number of plies	N	3
End tangent Length	L_T	13.000 mm
Fatigue Strength Reduction Factor	K_q	1.500

The design and theoretical analysis of metal expansion bellows is performed as per ASME standards. Fig.1 shows the direction of different stresses induced in metal expansion bellows. According to ASME standards, the circumferential membrane stress (S_1) in bellows tangent due to internal pressure is given as per Eq.1.

$$S_1 = \frac{1}{2}\frac{Lt\ Eb\ K\ P(Db + n\ t)^2}{[n\ t\ (Db + n\ t)\ Lt\ Eb + t\ c\ Dc\ L\ c\ Ec\ K]} \quad \ldots\ldots\ldots\ldots(1)$$

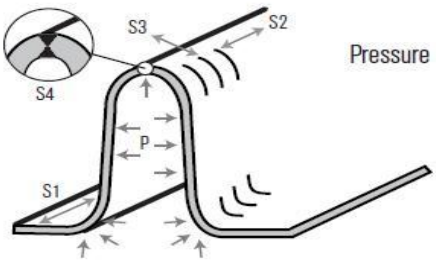


Fig. 1 Stress directions in bellows

The end convolution circumferential membrane stress (S2) due to internal pressure based on the equilibrium considerations as shown in Fig.2. The Eq.2 represents the end convolution circumferential membrane stress.

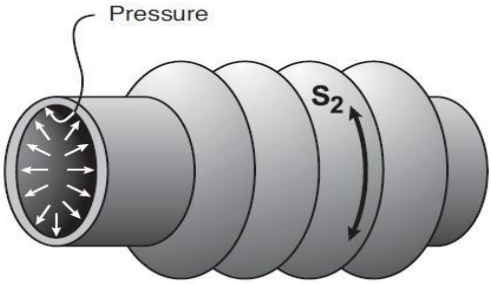


Fig. 2 Deflection stresses acting on bellows

$$S_2 = \frac{1}{2}\frac{P\,[q\ Dm\ Lt\ (Db\ n\ t)]}{E\,(A\ n\ t_P\ Lt + t\ c\ Lc)} \quad \ldots\ldots\ldots\ldots(2)$$

Where D_m is mean diameter of bellows convolution and it is given as;

$$Dm = Db + w + n \times t$$

The intermediate convolution circumferential membrane stress (S2,I) due to internal pressure is calculated by using Eq.3.

$$S_{2\,I} = \frac{1}{2}\left(\frac{P\,q\ Dm}{A}\right) \quad \ldots\ldots\ldots\ldots(3)$$

The bellows meridional membrane stress (S3) due to internal pressure is calculated based on the component of pressure in axial direction acting on the convolution divided by the metal area of root and crown by using Eq.4.

$$S_3 = \frac{1}{2}\frac{W\,P}{n\ t_p} \quad \ldots\ldots\ldots(4)$$

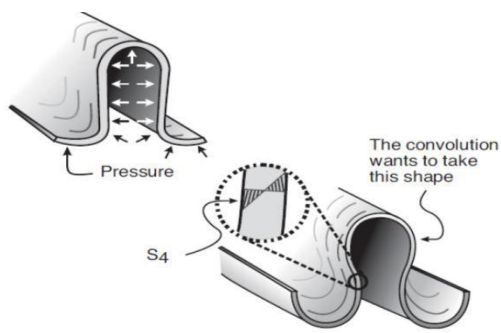


Fig.7 Stages of Analysis

Fig.3.Bending Stress Acting on Bellow

The bellows meridional bending stress (S_4) due to internal pressure as represented in Fig.3 is given by Eq.5. Fig.4 shows the variation of bending stresses induced in bellows.

$$S_4 = \frac{1}{2 \times n} \times \frac{w^2}{t_p} \times P \times Cp \quad \text{.....(5)}$$

The bellows meridional membrane stress (S_5) and meridional bending stress (S_6) due to deflection are given by the Eq. 6 & Eq.7. Fig.4 shows the representation of meridional bending stress.

$$S_5 = E_b \times t_p^2 \times \frac{\Delta Q}{2.0 \times w^3 \times C_f} \quad \text{.....(6)}$$

$$S_6 = 5 \times E_b \times t_p \times \frac{\Delta Q}{3.0 \times w^2 \times C_d} \quad \text{.....(7)}$$

Where C_p, C_f and C_d are the factors for calculating S_4, S_5, S_6 respectively. E_b is modulus of elasticity for bellows. Fig.5 shows the metal expansion bellows under consideration in this paper.

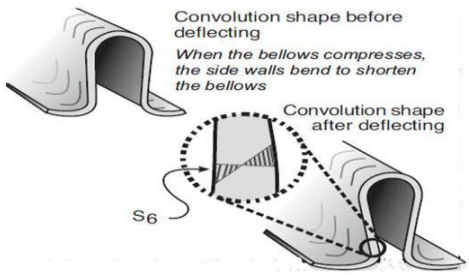


Fig.4. Bending stresses acting on bellows

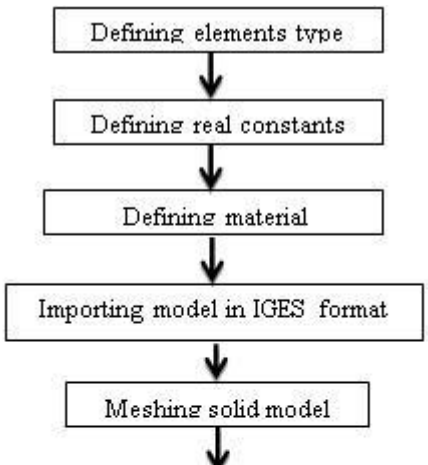


Fig.8 shows the meshed model of metal expansion bellows. In this work structural solid element 20 node plane183 element was used as element type. Elastic analyses were carried out on full convolutions of the bellows with axysimmetric model. The computational domain is divided into 10 elements in thickness and 200 elements in length. Therefore, the model with elements 10x200 is used in all analyses. In the present analysis, a U-shaped bellows named VLC Shell Dia. 129 is picked. The bellows inside diameter is 131 mm with outside diameter of 147 mm, thickness of 0.9mm, pitch of 8.00 mm, and height of the convolution is 8.00 mm. The bellows material is made of stainless steel SA-240 321 with the modulus of elasticity of 195GPa and

Poisson's ratio of 0.3. In this work the internal pressure in applied by applying the constraints.

V. RESULTS AND DISCUSSIONS

A. *Numerical validations*

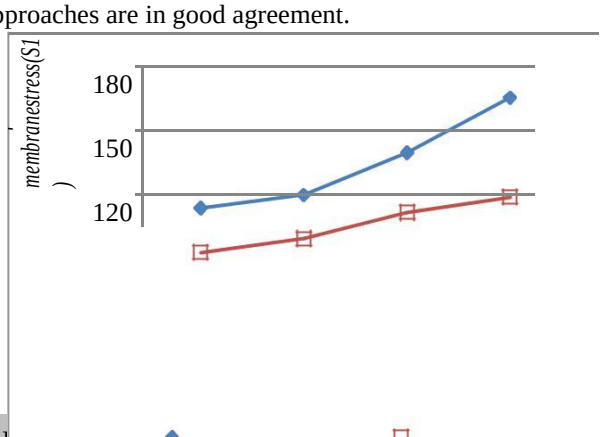
Comparison test is performed for verification of the results obtained by numerical method. For the given solid element FEM stresses are evaluated. The circumferential membrane stress at bellow tangent, intermediate and end convolution membrane stress, meridional membrane stress and meridional bending stress due to internal pressure of U-shaped bellows were calculated. The applied internal pressures are 1MPa, 1.12MPa, 1.5MPa and 2MPa, respectively. In the Table2, the results obtained from analytical approach and numerical simulations are presented. The meridional membrane stress and meridional bending stress for various internal pressures are presented in Table2. After comparing result it is observed that the obtained stresses by two approaches for U-shaped bellows are in good agreement and shows very close match.

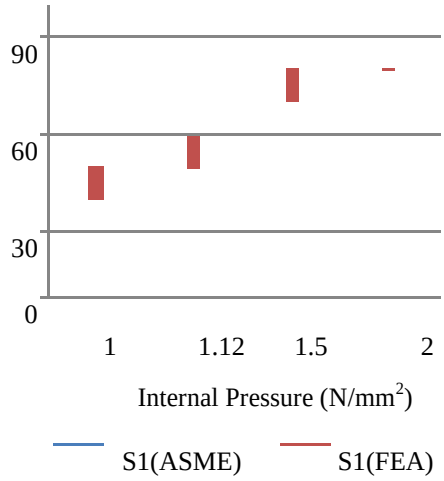
TABLE II
ANALYTIC AND FEA STRESSES DUE TO INTERNAL PRESSURE

Stress	Source	Internal Pressure (MPa)			
		1	1.12	1.5	2
S1	ASME	73.26	82.05	109.89	146.52
	FEA	43.83	53.02	70.26	80.53
S2I	ASME	31.28	35.03	46.92	62.56
	FEA	34.55	32.12	48.63	57.67
S2E	ASME	48.52	54.35	81.52	163.05
	FEA	42.36	34.44	61.46	86.41
S3	ASME	4.89	5.14	6.56	9.19
	FEA	30.39	33.26	45.41	61.85
S4	ASME	82.18	92.04	123.28	164.37
	FEA	33.12	31.73	47.48	54.68

B. Comparison of induced design and simulated stresses of metal expansion bellow

In the present work numerical values are used for evaluation of characteristics of metallic bellow. Initially the circumferential membrane stress is visualized with for variation of internal pressure. As per the requirement the internal pressures selected are 1 MPa, 1.12 MPa, 1.5 MPa and 2 MP are respectively. Fig.9 shows comparison of circumferential membrane stress induced in bellow tangent due to internal pressures of magnitude 2Mpa. Similar plot are obtained for various pressures as 1MPa, 1.12MPa, 1.5MPa. Comparison of different stresses for various values pressure is explained in Fig.10 to Fig.14. From Fig.10 it is seen that the circumferential membrane stress obtained by both approaches shows considerable variation in induced stress, but as design criterion which is within acceptable agreement. This is an important membrane stress that runs circumferentially around the bellows. For safety the value must be lower than the allowable stress for the bellows' material multiplied by the bellows' longitudinal weld joint efficiency. Fig.11 shows variation of intermediate convolution circumferential membrane stress due to internal pressure. From Fig.11 it is observed that the intermediate convolution circumferential membrane obtained by both approaches shows very closed match. This means that the stresses obtained by both approaches are in good agreement.





From Fig.12 it is seen that the end convolution circumferential membrane stress obtained by both approaches shows considerable variation as pressure varies from 1.12Mpa to 2MPa, but as per design criterion this is within acceptable limit, but the end convolution circumferential membrane stress obtained by both approaches shows much closed match for pressure 1Mpa. This means that the stress obtained by both approaches is in good agreement.

Fig.13 shows the variation of meridional membrane stress due to internal pressure. It is seen that the meridional membrane stress obtained by both approaches shows considerable variation in induced stresses, but as design criterion this is within acceptable limit. From Fig.13 it is observed that the calculated meridional membrane stress as per ASME standard almost remain constant as pressure varies from 1Mpa to 2Mpa, but the simulated meridional membrane stress increases significantly as pressure increases from 1Mpa to 2Mpa.

VI.CONCLUSION

It is seen that the meridional bending stress obtained by both approaches shows considerable variation in induced stresses, but as design criterion this is within acceptable limit. From Fig.14 again it is found that the calculated meridional bending stress as per ASME standard almost remain constant as pressure varies from 1Mpa to 2Mpa, but the simulated meridional bending stress increases significantly as pressure increases from 1Mpa to 2Mpa.

obtained as per ASME standard are compared with the FEA for stress distribution. The design stresses and distributions are compared for U-shaped bellows. The main conclusion is that the most destructive stress in bellows due to internal pressure is meridional bending stress and circumferential membrane stress. The circumferential membrane stress is an important membrane stress that runs circumferentially around the bellows. For safety the value must be lower than the allowable stress.

ACKNOWLEDGEMENT

Authors would to thank Mr. Umesh Ubarhande, *Sr. Manager, (R&D, PEM)* of Alfa

Laval India Pvt. Ltd, Pune for helping us in formulating the problem, providing the necessary input and guiding to achieve the objective.

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